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INNOVATION FOR SUSTAINABLE ACCELERATING SYSTEMS: THE EUROPEAN iSAS PROJECT*

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Abstract

If particle accelerators have largely proven their value to society, they must now meet the challenge of energy sustainability. The European project to *Innovate for Sustainable Accelerating Systems* (iSAS) is dedicated to energy-saving of superconducting radiofrequency (SRF) accelerating systems. iSAS will develop, prototype and validate new impactful energy-saving technologies so that SRF accelerators can operate with the same or improved performance with significantly less energy.

INTRODUCTION

Particle accelerators are essential instruments for research infrastructures and for a variety of applications, accounting for 40,000 machines worldwide. In a context of sustainability, minimizing the energy consumption of accelerators is an unavoidable challenge. Funded by the EU (HORIZON-INFRA-2023-TECH-01-01), the project to *Innovate for Sustainable Accelerating Systems* (iSAS) was launched in 2024 to develop core technologies of SRF accelerating systems to minimize energy consumption [1]. It is complementary to other programs developing energy-efficient magnets or RF sources.

This project gathers 12 research laboratories or institutes (CEA, CERN, CNRS, DESY, EPFL, ESS, HZB, INFN, NIKHEF, UKRI, univ. Brussels, univ. Lancaster) as well as 6 industrial companies (ACS, Cryolectra, Euclid Tech labs, Research Instruments, Thin Film Equipment, Zanon) over a 4-year duration. The iSAS project addresses 3 key Technology Areas with substantial potential to reduce the energy consumption of accelerators:

- energy-saving from RF power, through coherent integration of the RF power source with smart digital control systems and with novel tuners that compensate rapidly cavity detuning from mechanical vibrations,
- energy-saving from cryogenics to develop superconducting cavities with high performance at 4.2 K instead of 2 K, thereby reducing the grid-power to operate the cryogenic system,
- energy-saving from the beam power, to enable efficient energy recovery of recirculating beams in superconducting cavities with couplers to damp the Higher-Order Modes (HOMs) excited by the passage of high-current beams in the cavities.

Enabled by its large consortium and the joint investment between research institutions and industry, iSAS envisages three Integration Activities to introduce these energy-saving Technology Areas into research facilities:

- integration into a sustainable cryomodule design, by addressing common engineering challenges to use the technologies on a parametric cryomodule design,
- integration into existing research infrastructures, by retrofitting existing accelerating systems. A cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in the PERLE research facility,
- integration into industrial solutions, with concrete co-developments with industry to expedite high Technological Readiness Level (TRL) for large-scale deployment of the new energy-saving solutions at current, future infrastructures and towards industrial applications.

The iSAS project concentrates on SRF accelerating systems with the largest leverage for energy savings. The developed technologies aim to optimize:

- ferro-electric fast reactive tuners,
- low-level radio frequency control system,
- coatings of Nb_3Sn on Cu cavities,
- couplers (fundamental, higher-order modes) and beam line absorbers.

iSAS aims to perform R&D on these technologies and to promote their implementation towards industry, by raising their TRL. Three main accelerator-driven ESFRI RIs are at the core of iSAS: ESS, EuXFEL and HL-LHC.

This paper presents the main technologies under development and the description of the work to be performed by the different laboratories within the work packages (WPs) of iSAS. The focus is set on the metric to evaluate the expected energy saving for each of these devices.

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ENERGY SAVING METRIC

At the beginning of the project, a metric for energy saving performances of the different technologies was defined. This metric will be filled in at the end of the project, with the equipment available and operational at that time. For this metric, the selected approach is focused on the power required for operation. We will evaluate and compare the electrical power consumption with and without the iSAS technology under similar conditions. The comparison will be performed for different use cases (specific to each technology), but always under similar conditions for each technology to ensure a fair comparison [2]. In addition, a consumption model of the PERLE ERL will be developed to evaluate the accelerator efficiency.

FERRO-ELECTRIC FAST REACTIVE TUNER

In WP1 led by HZB, a fast-tuning system is developed to compensate detuning due to mechanical vibrations or beam induced transients, which are both usually compensated by adding a significant power overhead. Ferro-Electric Fast Reactive Tuners (FE-FRTs) are an alternative to classic mechanical cavity tuners (piezo). They form a coupled system of cavity and a typically coaxial line with ferro-electric material. The permittivity of this material is changed by applying high voltage, thus generating a change of impedance allowing to control the resonance frequency of the coupled system on a very fast time scale (~ 100 ns with a tuning range in the tens of kHz) [3, 4]. FE-FRTs require an additional RF port to install on the cavity, but avoid complex control algorithms needed to take into account the highly resonant mechanical-RF cavity-tuner system. FE-FRTs should of course not compromise stability or reliability of operation, but could even better improve it beyond current state-of-the-art.

FE-FRT will be tested with a 2-cell 1.3 GHz cavity and a fully equipped nine-cell TESLA/XFEL cavity, including a tunable high-power coupler and classic mechanical tuning system. The metric to estimate the savings is the invested RF power to drive the cavity at a given field (peak and average power) for microphonics compensation, which will be converted to wall-plug power. It will be determined by comparing the RF power invest with the FE-FRT and without the FE-FRT (with the piezo control) at identical values of loaded quality factor Q.

Expected savings in RF power should be significant. The required power to operate a cavity at voltage scales with the square of the cavity bandwidth in low beam loading machines (microphonics case). For an EU-XFEL cavity operated at 25 MV/m (CW mode), a factor of 10 reduction in RF power is expected when reducing the cavity detuning from 40 Hz half-bandwidth (typical with piezo tuners) down to 5 Hz, which is reachable with a FE-FRT.

SMART LLRF

In WP2 led by DESY, an optimized Low-Level Radio Frequency (LLRF) system is developed in order to reduce the RF power required to drive the cavities, thanks to an efficient control of cavity field and detuning. To minimize the RF power, cavities must operate at a quality factor Q_{ext} as high as possible, at a narrower bandwidth. But these conditions make resonance control extremely challenging and will only reduce the RF power needs if the resonance can be properly guaranteed. So, the challenge is to find the highest Q_{ext} ($\sim Q_L$) while meeting resonance control goals and without compromising operability or reliability. AI will be integrated in this smart LLRF. Moreover, FE-FRT will also help to reach high values of Q_{ext}.

Since a LLRF system is constantly required for cavity field control, the system cannot be switched OFF for comparison purposes. Yet, options of the optimized LLRF can be switched ON/OFF or adjusted to evaluate their impact on power consumption. Several factors of the LLRF tuning system impact the consumption of the accelerator (value of coupling, shape of the modulator pulse, efficiency of the frequency control, type of amplifier, drain voltage) so several metrics will be used: instantaneous AC consumption, RF power usage, AC-to-RF efficiency, accelerator up time. Measurements will be performed at different facilities (DESY, HZB and CNRS) offering different test options (CW, pulsed, presence of beam, narrow bandwidth cavities, etc.) to cover multiple operational cases.

Optimization using the LLRF system can lead to significant savings in the electrical power of an accelerator. For example, the step-wise optimization of the modulator pulse shape at the EU-XFEL led to a significant reduction in accelerator power consumption by more than 1 MW (Fig. 1). This improvement translates into cost savings of several million euros on the yearly electrical bill [5].

Significant savings in RF power are expected for the smart LLRF system developed within iSAS. For example, optimizing the working point of a GaN solid-state power amplifier with the LLRF can boost its efficiency from 55% to 65%. Increasing the external quality factor (Q_{ext}) of a cavity operating at 20 MV/m from Q_{ext} = 1e7 to Q_{ext} = 4e7 can reduce the required power from 10 kW to 4 kW.

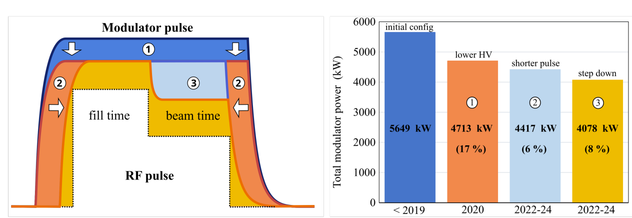

Figure 1: Left: optimization steps of the modulator pulse at EU-XFEL; right: corresponding power savings [5].

COATINGS ON COPPER CAVITIES

In WP3 led by INFN, iSAS will explore coatings of Nb_3Sn thin films on copper substrate aiming to operate RF cavities

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at a temperature higher than 2 K, thus reducing dramatically the required cryogenics power [6]. To match the excellent performances obtained with cavities made of bulk Nb at operated 2 K, thin film coatings must minimize flux trapping and ensure sufficient mechanical strength to allow for cavity tunability. These R&D topics will be studied on different types of samples and eventually with a cavity operating at 4.2 K developed within iSAS.

A cavity in operation generates losses ($\propto 1/Q_0$) which must be dissipated by the cryogenic circuit. Given the coefficient of performances (COP) of the cryogenic system, dissipating these losses requires a large amount of power: about 800 W of power at room temperature is needed to account for 1 W of power dissipated at 2 K (Fig. 2). The efficiency, or quality factor, of the cavity is driven by its surface resistance R_s via $Q_0 = G/R_s$ (G is the cavity geometry factor). The surface resistance depends on several parameters (sputtering coating parameters, copper substrate surface treatments, interlayer, post-coating treatments). It comprises a temperature-dependent term (BCS) and the residual resistance: $R_s = R_{BCS}(T) + R_{res}$. The BCS term can be calculated as a function of temperature, therefore the residual resistance R_{res} can be deduced from a usual measurement of Q_0 at a given temperature.

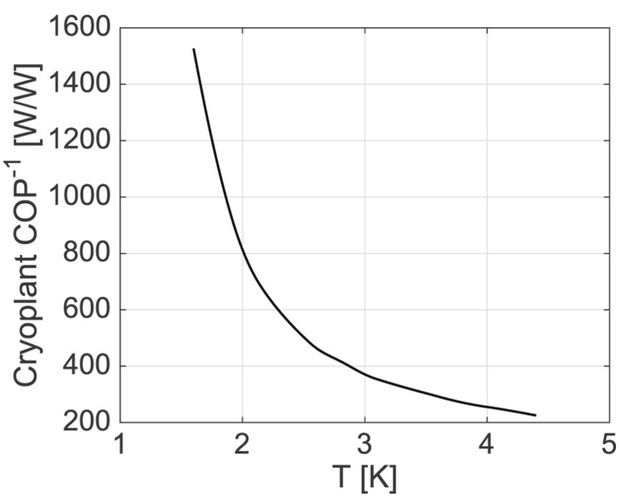

Figure 2: Typical cryogenic plant efficiency (watts of wall power to remove one watt of heat) as a function of temperature, accounting for Carnot efficiency and deviation of a realistic plant from Carnot [6].

The energy required to operate a multi-cell cavity can be characterized by the power dissipation of the cavity cell at a given accelerating field: P_{acc} per cell. This parameter accounts for both performance of the material (R_s) and the cryogenics system (COP). To estimate energy performance, we will determine the dissipated power for a Nb_3Sn coated cavity P_{acc} per cell at 1 MV/m as follows:

- Measure Q_0 versus E_{acc}, via an RF test, to deduce the surface resistance R_s at the given gradient,
- From this surface resistance evaluation of Nb_3Sn, estimate the power dissipation at 4.2 K,
- Comparison with bulk Nb at 2 K at same gradient by estimating the power dissipation at 2 K.

Three cases will be studied: quadrupole resonators QPR (400 MHz, 800 MHz), 1.3 GHz cavity (baseline of the I.FAST project [7]) and a new cavity optimized in ISAS.

With material having a higher critical temperature, it is envisaged that SRF cavities be cooled at 4.2 K while maintaining high quality factor Q_0 and accelerating field E_{acc}. Given the efficiency of the cryogenics system ($\simeq$ 240 at 4.2 K versus $\simeq$ 800 at 2 K), running at 4.2 K instead of 2 K would reduce the power consumption by a factor of 3. The expected grid power ranges between 1-3.5 W per cell at 1 MV/m for R_{res} = 5-30 nΩ (Fig. 3). Thus, a Nb_3Sn cavity operated at 4.2 K outperforms a Nb cavity at 2 K, even at a residual resistance up to 5-6 times higher.

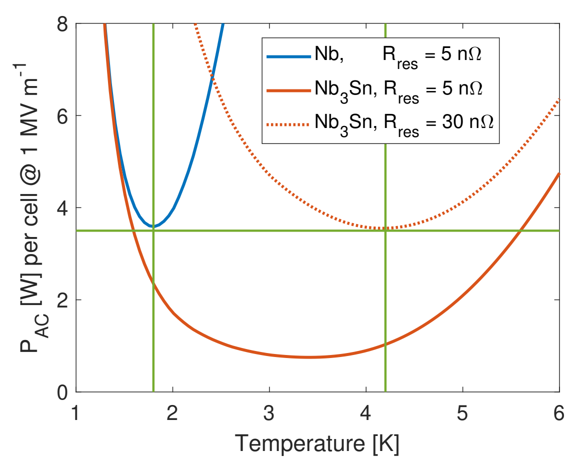

Figure 3: Calculated AC power of Nb and Nb_3Sn cavity cells versus temperature at 1.3 GHz [8].

COUPLERS

In WP4 led by CNRS dedicated to couplers, different technologies and devices are developed, mainly at 800 MHz. They will be designed, integrated and tested in accelerator-like conditions in a cryomodule capable of energy-recovery operation at the PERLE facility (Fig. 4):

- Fundamental Power Coupler (FPC) to introduce the power to excite the fundamental mode of the cavity via an antenna, in order to accelerate the beam,
- Higher Order Modes (HOM) coupler to damp the HOMs trapped in the cavity and deposit them into loads at higher temperatures.
- Beam Line Absorber (BLA) to damp HOM propagating out of the cavity, through the beam pipes by absorbing directly their power.

The cooling strategies for these components aims at reducing the heat loads to the cryogenic bath, while preserving the functional RF requirements. Even a moderate fraction of HOMs dissipated in the cryomodule's cold mass, will increase significantly the grid power for cryogenics. Optimizing the design of RF couplers is of particular importance

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as FPCs and HOMs can account for half of the cryogenic load on a linac, as estimated on the Cornell CBETA ERL linac [9].

Optimization of the electric consumption for cryogenic process mainly depends on heat loads and temperatures involved. It requires fine thermal simulations and selection of the optimized cooling processes. When additional components are required, the complexity of this new component must also be considered. For example, introducing BLA may induce a potential risk of particle contamination in the cavities due to the vicinity of the BLA material and may impose specific venting precautions for this material. For the metric, we propose to calculate the electrical power consumption of the cryogenic system for different cases. The final estimation of the plug power will use the overall real efficiency of the actual cryoplant of PERLE.

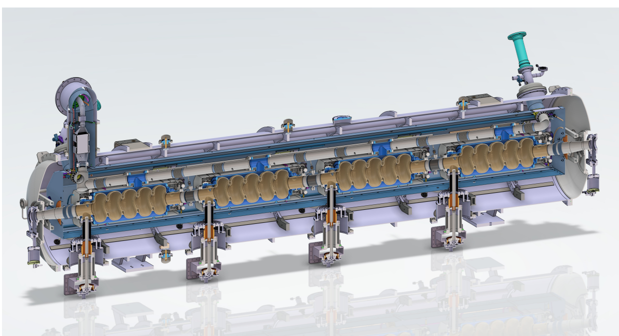

Figure 4: Cryomodule design of the energy recovery linac project PERLE with FPC, HOM coupler and BLA [10].

Fundamental Power Coupler

At 800 MHz, the power coupler uses the design of the SPL coupler considering its high RF power range and high efficiency of the heat exchanger [11]. The comparison between turbulent and laminar regimes was evaluated to select the best cooling regime. Furthermore, two cooling schemes are studied and their cooling-power consumption compared. For these two schemes, we consider, as a first approximation, that the solid conduction heat from the cold part of the FPC external conductor to the 2K bath is equal in both cases:

- Two-loop coupler (heat exchangers at 50 K and 5 K),
- One-loop coupler (heat exchanger from 5 K to 300 K).

With a given RF design, cooling scheme optimizations include materials to reduce the solid conduction (stainless steel body) and RF losses (copper coating). The one-loop cooling scheme is selected as it is about 2.5 times energetically more efficient than the two-loop scheme. It is important to note that the energy saving obtainable with the one-loop cooling scheme with helium is strictly connected with the helium inlet temperature in the double-walled tube, which should be as close as possible to the design value of 5 K.

To complete the design work performed on the FPC itself, analyzing the data from the ESS cryomodule provides valuable feedback to further optimize the FPC system by improving the thermal insulation of the cryogenic line to the FPC.

Higher Order Modes Couplers

Higher order modes can be excited in cavities by the high-power beams. They must be handled with care as improper extraction of HOMs can strongly limit the beam intensity due to beam instabilities. Energy-recovery linacs (ERLs) are particularly subject to HOMs excitations due to recirculation of high-current beams in the superconducting cavities.

At 800 MHz, the HOM studies have been made for three different designs: hook, probe and double quarter-wave [12]. The selected scheme uses 2 hook HOM couplers per cavity. For the metric, two cooling schemes will be studied and their cooling power consumption compared:

- HOM coupler cooled at 2 K,
- HOM coupler cooled at 5 K.

HOM optimizations include geometrical design: RF optimization (to reduce the RF losses) and thermal design, flange type and material, heat interception on the RF wire as well as materials to reduce the surface resistance and consequently the RF losses. For high RRR Nb, the surface resistance is several orders of magnitude higher at 5 K than 2 K. Thus, a cooling at 5 K could be energetically efficient only with superconducting materials other than Nb, for instance Nb_3Sn which would require dedicated R&D.

It is important to mention that cooling at 5 K can compromise the functionality of the HOMs. In case of unexpected heat loads, the antenna could quench. Therefore, even if a cooling at 5 K is more efficient, the 2 K option may still be preferred because of a higher reliability against unexpected loads.

Beam Line Absorbers

Beam Line Absorber are used to damp the higher order modes propagating out of the cavity, through the beam pipes. The BLAs are designed to absorb directly the power generated by the HOMs.

At 800 MHz, the BLA studies are underway to define the optimum design to integrate in the cryomodule to be tested at the PERLE facility. For the metric, three cooling schemes will be studied and their cooling power consumption compared:

- Without BLA inside the cryomodule (BLA at 300 K),
- With BLA inside the cryomodule (BLA at 50 K),
- With BLA inside the cryomodule with an intermediate thermal intercept at 5 K (BLA at 50 K).

In the first scheme, the maximum possible dissipation could be too high for the cryoplant to withstand.

In the second scheme, the power dissipated in BLAs by the HOMs is high (~50W between each cavity) but controlled. The BLAs are placed in between each cavity. Some absorber materials have a good efficiency when cooled at 50 K (temperature loop provided by the cryoplant), but require R&D. When cooling the inter-cavity space at 50 K, residual solid conduction heat is evacuated at 2 K.

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In the third scheme, an intermediate 5 K interception loop is added to the previous option. BLA optimizations include the geometrical design and R&D on microwave absorbing material cooled at 50 K. BLAs will be placed in the cryomodule. Depending on the final inter-cavity and the BLA mechanical integration, the 5 K interception could be avoided to thus circumventing the complexity and the heat losses due to an additional transfer line at 5 K.

ENERGY RECOVERY LINAC

Energy-recovery linacs are a promising technology and accelerator concepts to provide high current, high brightness and high-quality beam by minimizing the accelerator power consumption and footprint [13]. One key aspect is that the ERL concept enables to recover the beam power of the accelerated beam after the interaction point (IP), thus reducing the RF requirements compared to classical acceleration with single-pass linacs. To provide an order of magnitude of this power saving, one can consider the ERL of the PERLE project as a reference example. PERLE aims to provide a CW 20 mA electron beam at 250 MeV at the IP (5 MW) [14] with one cryomodule composed of 4 cavities.

A consumption model of the PERLE ERL will be developed to determine the accelerator efficiency. The goal is to evaluate this beam power at the IP as a fraction of total electricity consumption. This efficiency will be calculated with the best accuracy considering all the elements of the machine and impacts of errors due to perturbations (i.e. microphonics) or synchronization (path length adjustment). The same exercise will be applied to a classical linac solution and compared to the ERL efficiency.

CONCLUSION

With the European project iSAS (2024-2028), impactful energy-saving technologies will be developed, validated and integrated with a direct impact on current research infrastructures, their upgrades as well as future industrial solutions. The project concentrates on SRF accelerating systems with the largest leverage for energy savings.

The devices under optimization by the participating institutions include ferro-electric fast reactive tuners, AI-driven low level radio frequency control system, coatings of Nb_3Sn on Cu cavities, couplers (fundamental, higher order modes) and beam line absorbers. Moreover, iSAS will provide a complete accelerating structure capable of accelerating high-power beams in an energy-sustainable way: a cryomodule at 800 MHz to be tested at the ERL PERLE facility.

A detailed and concrete plan to evaluate the energy-saving metric of all the technologies developed is defined. It is the long-term ambition of iSAS to reduce the energy footprint of future SRF accelerators by half.

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